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Gain Coefficient Calculations for Laser lines Emission in C-like Se (XXIX)

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Abstract— **By using the fully relativistic flexible atomic code (FAC) program to calculating the energy levels, transition probabilities, oscillator strengths, and collision strengths for Se (XXIX). These data are used in the determination of the reduced population for the 69 fine structure levels belonging to the configurations[$2s^2$ $2p^2$, $2s^2$ 2p 3l (l= s, p &d) and 4l (l=s,p,d,&f)] in C-like Se (XXIX) and gain coefficients over a wide range of electron densities (from 10^{+20} to $10^{+22}cm^{-3}$) and at various electron plasma temperatures (500,1000,1500,2000,2500)eV. The results show that the transitions in Se (XXIX) ion to be the most promising laser emission lines in the XUV and soft X-ray spectral regions.**

Index Terms— **population inversion, laser radiation, XUV, Soft X-ray, gain coefficient**

I. INTRODUCTION

The last three decades have been seen enormous advancement in our understanding and developing high efficiency of X-ray with gain [1, 2]. The original mechanisms proposed for demonstrating X-rays lasing was via resonant photo pumping where many scientists have been studied this lasing mechanism [3]. Generally carbon is abundant element in astrophysical objects including the Earth's atmosphere. Emission lines of C-like ions are useful in the diagnosis of the solar, astrophysical and fusion plasma; and their interpretation requires accurate atomic data [4].

Since 1986 atomic data and spectral line intensities for C-like ions were studied, which calculated the oscillator strengths, radiative decay rates and electron collision. Several authors have studied this lasing mechanism experimentally and theoretically [3–5], in the hope of developing high-efficiency X-ray laser. Energy levels, radiative decay rates and oscillator strengths have been calculated for the C-like Se (XXIX) by Feldman et.al [6, 7].

But no much work has been done to predict the gain of C-like Se theoretically. The aim of this work is to study the possibility of obtaining laser in the XUV and soft X-ray region in C- like ions. The fully relativistic flexible atomic code(FAC) program[8] approach based on Dirac equation have been used to calculate the energy levels, transition probabilities, oscillator strengths, and collision strengths. These data are used in the determination of the reduced population for the 69 fine structure levels in C-like ion of Se XXIX and gain coefficients over a wide range of electron densities and at various electron plasma temperatures. The atomic data are used further to investigate the production of short wavelength lasers in the XUV and the soft X-ray spectral regions. According to applied the electron collisional pumping to the ground state, the inversion factors can be calculated and the gain coefficients for those transitions that have positive population inversion have been calculated. These leading us to successful results of atomic structure and ionizing phenomena which provide new laser lines in the XUV and X-ray spectral regions. The useful of these studies to help us to develop X-ray laser devices.

II. COMPUTATION OF GAIN COEFFICIENT

Laser emission possibility from plasma of Se XXIX ion via electron collisional pumping, in the XUV spectral region is investigated at different electron densities and plasma temperatures.

Densities of The reduced population are calculated by solving the coupled rate equations [9-11]

$$N_j\left[\sum_{i<j} A_{ji} + N_e\left(\sum_{i<j} C_{ji}^d + \sum_{i>j} C_{ji}^e\right)\right] = N_e\left(\sum_{i<j} N_i C_{ij}^e + \sum_{i>j} N_i C_{ij}^d\right) + \sum_{i>j} N_i A_{ij}$$

Where N_j and N_i is the fractional population of level j *and* i respectively, N_e is the electron density, A_{ji} is the Einstein coefficient for spontaneous radiative decay from j to i; and C_{ij}^e *and* C_{ji}^d represent the rate coefficient for collisional excitation and de-excitation respectively. The actual population density N_J of the j^{th} level can be calculated from the equation of identity [12, 13].

$$C_{ji}^d = C_{ij}^e\left[\frac{g_i}{g_j}\right]\exp\left[\frac{\Delta E_{ji}}{kT_e}\right] \qquad (2)$$

Where g_i and g_j are the statistical weights of the lower and upper levels, respectively.

The electron impact excitation rates usually are expressed via the effective collision strengths γ_{ji} as

$$C_{ji}^d = \frac{8.6287 * 10^{-6}}{g_j T_e^{1/2}}\gamma_{ij} \qquad (3)$$

Where the values of γ_{ji} and A_{ji} are obtained by [12].

The actual population density N_J of the j^{th} level is obtained from the following identity [12],

$$N_J = N_j * N_I \qquad (4)$$

Where N_I is the quantity of ions which reached to the ionization stage I [12],

$$N_I = f_I \, {}^{N_e}/Z_{avg} \qquad (5)$$

Where N_e is the electron density, Z_{avg} is the average degree of ionization and f_I is the fractional abundance of the ionization states which can be calculated from the relation [12].Since the populations calculated from Eq. (1) are normalized such that,

$$\sum_{j=1}^{69} \frac{N_J}{N_I} = 1 \qquad (6)$$

After the calculation of levels population density, the quantities N_j/g_j and N_i/g_i can be calculated.

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Once a population inversion has been ensured a positive gain through F>0 [14] is obtained by

$$F = \frac{g_j}{N_j}\left[\frac{N_j}{g_j} - \frac{N_i}{g_i}\right] \qquad (7)$$

Where N_j/g_j and N_i/g_i are the reduced populations of the upper level and lower level respectively. Eq. (7) has been used to calculate the gain coefficient (α) for Doppler broadening of the various transitions in the Se (XXIX) ion.

$$\alpha_{ji} = \frac{\lambda_{ij}^2}{8\pi}\left[\frac{M}{2\pi K T_i}\right]^{1/2} A_{ji} N_j\ F \qquad (8)$$

Where M is the ion mass λ_{ij} is the transition wavelength in (nm), T_i is the ion temperature in K and j, i represent the upper and lower transition levels respectively.

III. .RESULTS AND DISCUSSIONS

A. Level population

The reduced population densities are calculated for 69 fine structure levels arising from $1s^2\ 2s^2\ 2pnl$ (n=3, l=s, p&d) and ml (m=4, l=s, p, d& f) configurations that emit radiation in the XUV and soft X-ray spectral regions. The calculations were performed by solving the coupled rate Eq. (1) simultaneously using MATLAB version 7.10.0 (R2010a) computer program. The reduced population's density are calculated as a function of electron densities and plotted at different plasma temperatures for Se (XXIX) ion. The behavior of level population's density of the Se (XXIX) ion can be explained as follows: in general, at low electron densities the reduced population density is proportional to the electron density, where excitation to an excited state is followed immediately by radiation decay, and collisional mixing of excited levels can be ignored. This result is in agreement with that of Feldman et.al. [6,11,15]. At high population densities (10^{+21}), radiative decay to all levels will be negligible compared to collisional depopulations and all level populations become independent of electron density and are approximately equal (see figures 1 to 5). The10^{+19} electron density shows a peak at before the other levels then decreases to the saturation faster than the other levels, which mean that the nonradiative transitions dominant the de-excitation because of its higher energy and fast decay time. The population inversion is largest where electron collisional de-excitation rate for the upper level is comparable to radiative decay for this level [6, 15]

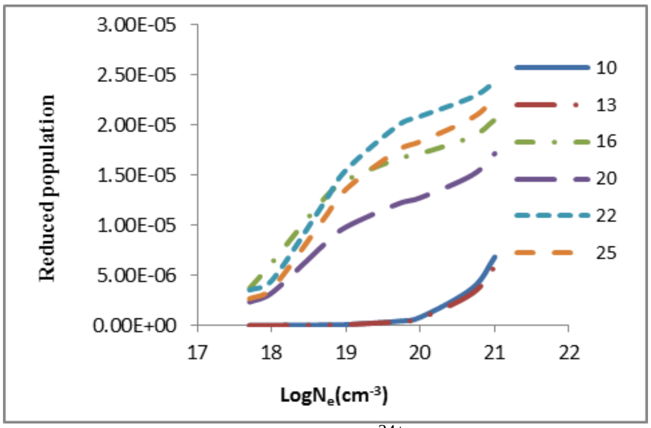

Fig.1 reduced population of Se^{34+} levels after electron collisional pumping as a function of the electron density at temperature 500 eV

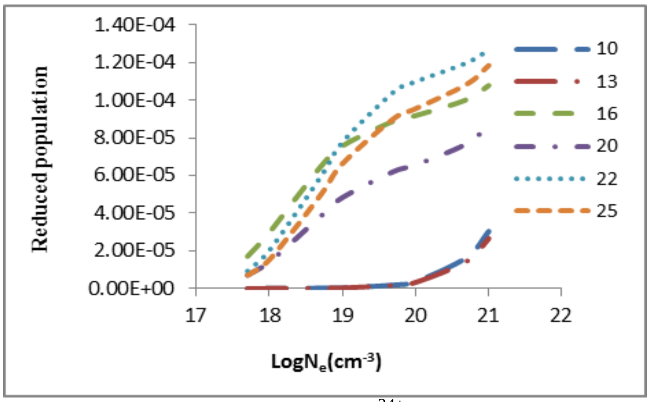

Fig.2 reduced population of Se^{34+} levels after electron collisional pumping as a function of the electron density at temperature 1000 eV

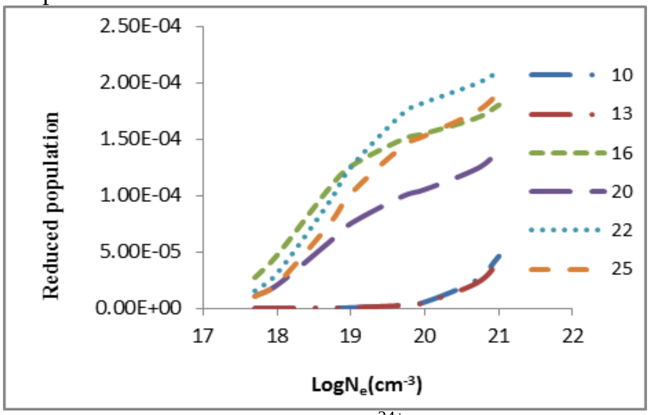

Fig.3 reduced population of Se^{34+} levels after electron collisional pumping as a function of the electron density at temperature 1500 eV

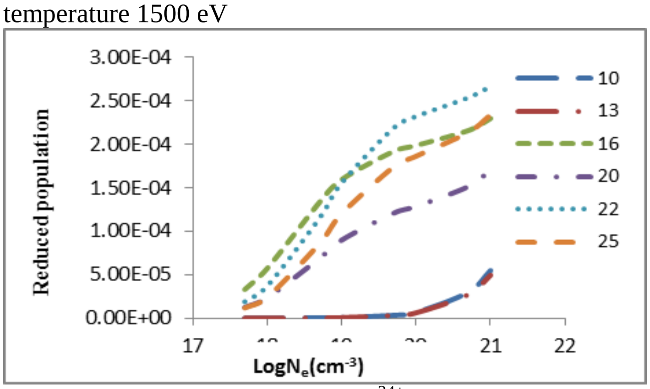

Fig.4 reduced population of Se^{34+} levels after electron collisional pumping as a function of the electron density at temperature 2000 eV

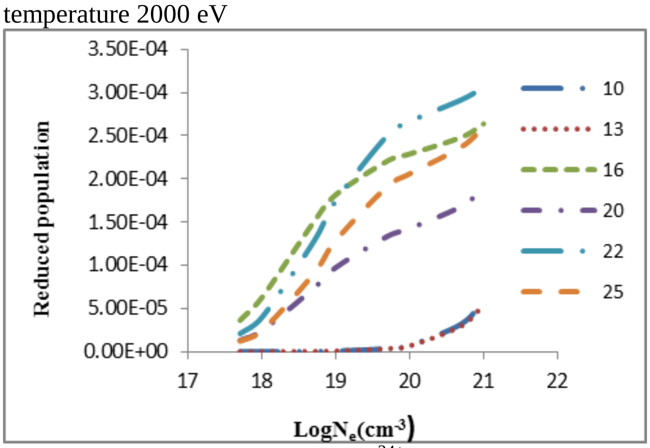

Fig.5 reduced population of Se^{34+} levels after electron collisional pumping as a function of the electron density at temperature 2500 eV

B. Radiative lifetime:

The lifetimes are determined almost entirely from the allowed and the strong inter combination transitions. The radiative lifetime τ_j of an excited atomic state j, is related to the atomic transition probability A_{ji} by:

$$\tau_j = \frac{1}{\sum_i A_{ji}} \quad (9)$$

Where the sum is extended over all the lower states which can be reached from the upper state by radiative decay. Table1. Contains the present results of radiative lifetime for the upper and lower laser levels for the Se (XXIX).

Table 1. Radiative lifetime for Se^{34+} laser levels

Configuration	τ_j(sec)	τ_i(sec)
$(2p_{1/2}3d_{5/2})_3$--$(2p_{1/2}3p_{3/2})_2$	2.6831E-14	1.4165E-10
$(2p_{3/2}3p_{3/2})_2$--$(2p_{1/2}3p_{3/2})_2$	9.1771E-11	1.4165E-10
$(2p_{3/2}3d_{3/2})_2$—$(2p_{1/2}3p_{3/2})_2$	2.6444E-14	1.4165E-10
$(2p_{1/2}3d_{5/2})_3$—$(2p_{3/2}3p_{1/2})_1$	2.6831E-14	2.4478E-10
$(2p_{3/2}3d_{3/2})_2$—$(2p_{3/2}3p_{1/2})_1$	2.6444E-14	2.4478E-10
$(2p_{3/2}3d_{3/2})_1$—$(2p_{3/2}3p_{3/2})_2$	1.7438E-14	9.1771E-11

C. Inversion factor

Laser amplification will occur only if there is population inversion, or in other words, for positive inversion factor F>0. In order to work in the XUV and X-ray spectral regions, we have selected transitions between any two levels producing photons with wavelengths between 5 and 100 ˚ A. The electron density at which the population reaches corona equilibrium approximately equals to A/D, where A is the radiative decay rate and D is the collisional de-excitation rate [14]. The population inversion is largest where the electron collisional de-excitation rate for the upper level is comparable to the radiative decay rate for this level.

D. Gain coefficient

As population inversion will be positive in laser medium. Eq. (8) has been used to calculate gain coefficient for the Doppler broadening of various transitions in the Se^{34+} ion. For F>0 transition having positive inversion with the maximum gain coefficient in cm^{-1} are calculated (see table 2). The maximum gain was calculated and plotted against electron density (see Fig. 6-10). These short wavelength laser transitions can be produced using plasmas created by optical lasers as the lasing medium. For Se^{34+} ion the rates for electron collisional excitation from the 1s2 2s2 2p2 ground state to the 1s2 2s2 2p 3l (l= s, p, d) configuration are greater than the rates for excitation from the ground state to the 1s2 2s2 2p 4l state. For electron densities and electron temperatures that are typical of laboratory high-density plasma sources this agreement with Feldman et al. [6], such as laser- produced plasmas, it is possible to create a quasi-stationary population inversion in this ion. Under favorable conditions large laser gains for this transition in the XUV and soft X-ray regions of the spectrum can be achieved in the carbon-like Se ion from our calculation. The gain calculations were performed at various electron temperatures and at various electron densities.

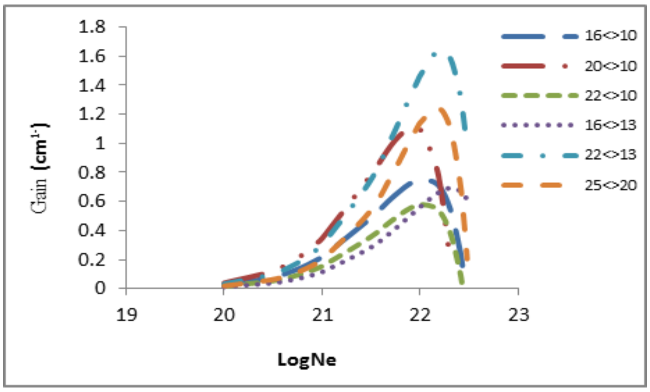

Fig.6 gain coefficient of possible laser transition against electron density at temperature 500eV in Se^{34+}

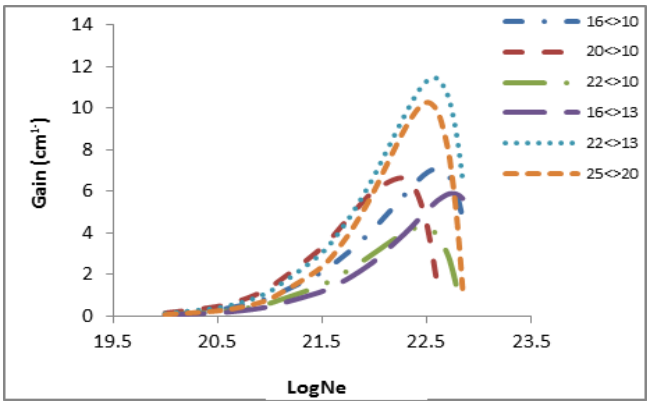

Fig.7 gain coefficient of possible laser transition against electron density at temperature 1000eV in Se^{34+}

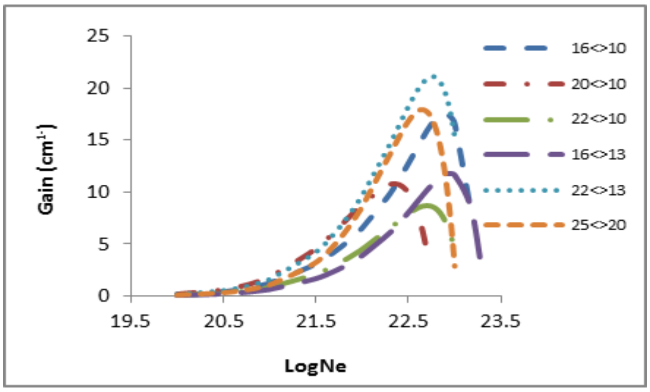

Fig.8 gain coefficient of possible laser transition against electron density at temperature 1500eV in Se^{34+}

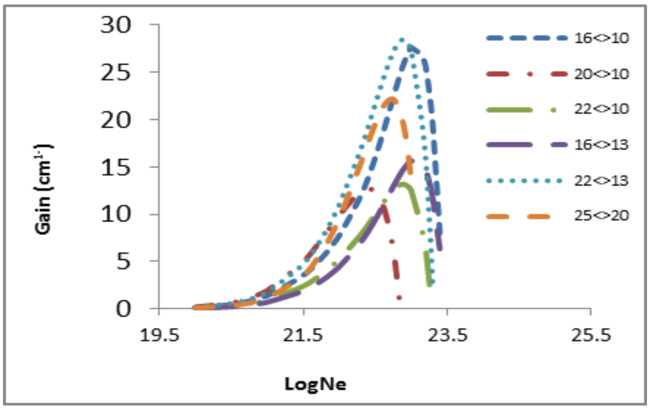

Fig.9 gain coefficient of possible laser transition against electron density at temperature 2000eV in Se^{34}

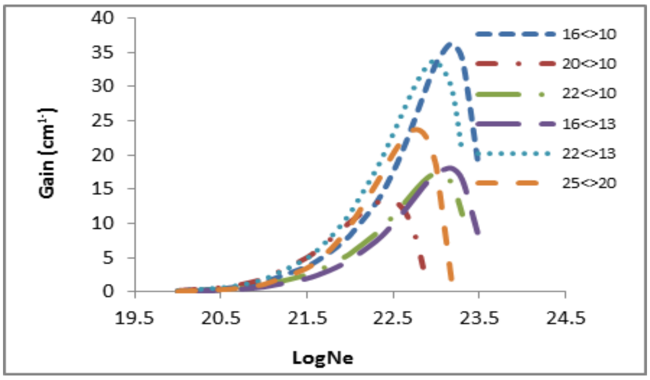

Fig.10 gain coefficient of possible laser transition against electron density at temperature 2500eV in Se^{34+}

IV. Conclusions

In this work the analysis that have been presented shows that electron collisional pumping (ECP) is suitable for attaining population inversion and offering the potential for laser emission in the spectral region between 22 and 50 nm for the Se^{34+}ion. This class of lasers can be achieved under the suitable conditions of pumping power as well as electron density. If the positive gains obtained previously for some transitions in the ion under study together with the calculated parameters could be achieved experimentally, then successful low-cost electron collisional pumping XUV and soft X-ray lasers can be developed for various applications. The results have suggested the following laser transitions in the Se^{34+} plasma ion (see Table 2), as the most promising laser emission lines in the XUV and soft X-ray spectral regions.

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Table2: Laser transitions, wavelength, and maximum gain coefficient at temperatures (500, 1000, 1500, 2000 and 2500) eV in the possible laser transitions. (Se XXIX).

Transition	Configuration	λ(nm)	Gain(α)(cm^{-1})				
			T=500(ev)	T=1000(ev)	T=1500(ev)	T=2000(ev)	T=2500(ev)
16<>10	$(2p_{1/2}3d_{5/2})_3$--$(2p_{1/2}3p_{3/2})_2$	30.92	0.754806	7.086808	17.54257	27.62928	36.32678
20<>10	$(2p_{3/2}3p_{3/2})_2$--$(2p_{1/2}3p_{3/2})_2$	45.18	1.111109	6.611263	10.74402	12.54568	13.38181
22<>10	$(2p_{3/2}3d_{3/2})_2$—$(2p_{1/2}3p_{3/2})_2$	63.84	0.581674	4.27753	8.705329	13.16876	17.38917
16<>13	$(2p_{1/2}3d_{5/2})_3$—$(2p_{3/2}3p_{1/2})_1$	19.58	0.69261	5.892579	11.77182	15.67094	18.07941
22<>13	$(2p_{3/2}3d_{3/2})_2$—$(2p_{3/2}3p_{1/2})_1$	34.87	1.635007	11.42846	21.09327	28.47305	33.82869
25<>20	$(2p_{3/2}3d_{3/2})_1$—$(2p_{3/2}3p_{3/2})_2$	23.87	1.245186	10.2352	17.80381	22.16988	23.73358

Where λ is the laser transition wavelength in (nm); α is the gain coefficient in cm^{-1}

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